

The Physical Parameters and Excitation of Jets and Knots in PNe

D. R. Gonçalves and A. Mampaso

*Instituto de Astrofísica de Canarias,
E-38205 La Laguna, Tenerife, Spain, Email: denise@ll.iac.es*

R.M.L. Corradi

*Isaac Newton Group of Telescopes,
Apartado de Correos 321, E-38700 La Palma, Spain*

M. Perinotto

*Dipartimento di Astronomia e Scienza dello Spazio,
Università di Firenze,
Largo E. Fermi 5, 50125 Firenze, Italy*

Abstract. We are carrying out a study of the physical parameters and excitation of low-ionization structures (LIS) in planetary nebulae (PNe). Since the optical morphology and kinematics of the LIS and the main components (rims, shells and haloes) of our sample were studied previously, our main goal now is to search for: i) the density contrasts between jets/knots and the main nebular components; ii) their main excitation processes; and iii) their chemical abundances. The first results of this survey — based on the analysis of NGC 7009, NGC 6543, NGC 6891 and K 4-47 — are that there is no significant density contrast between LIS and their surroundings, and that most of the LIS studied (but not all) are mainly photoionized, rather than shock excited.

1. Introduction

Our study is based on a sample of PNe with high quality images that allow us to separate the properties of jets/knots from those of the main components. Previous studies (Balick et al. 1994; Hajian et al. 1997) have attempted to access the nature of FLIERs (fast, low-ionization, emission regions) with similar analyses. We are now trying to extend the work to a larger sample of LIS (20 PNe), including not only FLIERs but also the other types of LIS. So far, we have analyzed only part of the sample and we describe our results here.

We obtained long-slit spectra of NGC 7009, NGC 6891, NGC 6543, and K 4-47 on August 2001 using the 2.5 m Isaac Newton Telescope at La Palma, Spain. We used the IDS, with a configuration such that the spectra cover the wavelength region from 3650 Å to 7000 Å, with spectral and spatial sampling of 3.3 Å pix⁻¹ and 0.70'' pix⁻¹. The spectra were wavelength and flux calibrated, corrected

Table 1. Physical Parameters of PNe with Jets/knots

Parameter	K1	J1	K2	R1	R2	K3	J2	K4	NEB
NGC 7009 (79°)									
Ne[SII] (cm^{-3})	2000	1300	4500	5500	5900	5000	1100	1300	4000
Ne[ClII] (cm^{-3})	-	-	4700	5200	5900	6000	1300	1900	4500
Te[OIII] (K)	9600	10400	9300	10000	10200	10100	11600	10400	10100
Te[NII] (K)	11000	-	9400	10400	12800	10400	-	11700	10300
Te[SII] (K)	7100	-	8300	-	-	-	-	9400	-
NGC 6543 (-5°)									
	J1	S1	R1	R2	S2	J2	NEB		
Ne[SII] (cm^{-3})	2000	9400	5200	6100	4800	1200	6400		
Ne[ClII] (cm^{-3})	6900	9200	7400	7100	5500	2500	6400		
Te[OIII] (K)	9700	7900	8000	7700	7500	9200	7900		
Te[NII] (K)	7500	8400	9100	9200	8900	7000	8400		
Te[SII] (K)	14200	7200	10400	16100	8700		
NGC 6891									
	J1(135°)	R1(45°)	R2(45°)	J2(135°)	NEB (135°)	NEB (45°)			
Ne[SII] (cm^{-3})	1400	2000	1000	1100	1300	1100			
Ne[ClII] (cm^{-3})	1100	2700	2600	...			
Te[OIII] (K)	8500	10000	10000	9500	9100	10000			
Te[NII] (K)	7500	9300	9500	10300	9800	9400			
K 4-47 (41°)									
	K1	Rim	K2	NEB					
Ne[SII] (cm^{-3})	5400	2100	2700	3200					
Te[OIII] (K)	24500	19200	16200	18900					
Te[NII] (K)	18300	24100	16800	20100					

for extinction, and then emission line intensities were measured allowing us to derive the physical parameters.

Note, from Table 1 of Gonçalves et al. (2001), that for most of the PNe in our sample good kinematical studies exist in the literature. They allow to compare the kinematical ages of the LIS with those of the main nebular shells, and in particular of the bright inner rims (created by the interaction of the AGB with the post-AGB winds). For two of the PNe (NGC 7009 and NGC 6891), the LIS and rims appear to be coeval; in NGC 6543 LIS are younger than the rim, and the pair of knots in K 4-47 is likely older than the nebular core. Generally, their orientations in space seems to coincide with the main axis of the axisymmetrical shells (‘polar’ flows), or a little tilted (by as much as 30° for those discussed here). With the exception of NGC 6891, the tips of all the other jets are located (in projection) outside the rim.

2. NGC 7009 and the Other PNe

In Table 1 we present the physical parameters ($N_e[\text{S II}]$, $N_e[\text{Cl III}]$, $T_e[\text{O III}]$, $T_e[\text{N II}]$, and $T_e[\text{S II}]$) for selected features of each PN. Note that “R” stands for rim, “S” for the shell attached to the rim, “J” for jet, “K” for knot, and “NEB” for the results associated with the emission integrated along the slit for the entire nebula. Position angles (P.A.) are also given in Table 1 (numbers that appear beside the PN or feature name).

NGC 7009: We selected six ‘microstructures’ in this PN (see Figure 2 of Gonçalves’s paper, this volume)— including the outer pair of knots (K1, K4), the pair of jets (J1, J2), the inner pair of knots (K2, K3), in addition to the rim (R1,

R2). Our main results are: i) the electron temperature throughout the nebula is remarkably constant, $T_e[\text{O III}] = 10\,200\text{ K}$; ii) the bright inner rim and inner pair of knots have similar densities of $N_e \approx 6000\text{ cm}^{-3}$, whereas a much lower density of $\sim 1500\text{ cm}^{-3}$ is derived for the outer knots and for the jets; iii) all the regions (rim, inner knots, jets and outer knots) are mainly radiatively excited; and iv) there are no clear abundance changes across the nebula for He, O, Ne, or S. There is a marginal evidence for an overabundance of nitrogen in the outer knots (ansae), but the inner ones (caps) and the rim have similar N/H values that are at variance with previous results.

The derived values for T_e , N_e and the abundances of the whole nebula (see NEB column in Table 1) are in fair agreement with previous determinations (Hyung & Aller 1995; Rubin et al. 2002). The properties of each region are more difficult to compare with other works because there are no previous studies of this PN which make such a detailed study of individual features of NGC 7009. But, again, for the positions for which these parameters are available, there is at least a marginal agreement with our values (Bohigas et al. 1994; Balick et al. 1994).

The fact that none of NGC 7009's features is shock-excited put in doubt the nature of its pair of jets. Are these real jets that are expanding supersonically through the halo? The failure to find evidence for shock excitation in the outer knots and jets might simply reflect their moderate velocities or, as discussed by Gonçalves et al. (2003), be in contradiction with the model predictions. However, very recently, two groups of researchers have studied in detail the kinematics of this PN and both find that the jets are indeed supersonic features (Fernández et al. 2003; F. Sabbadin, private communication).

NGC 6543: At variance with the other PNe in the sample, the electron temperatures of its jet are higher than those of the inner nebula, at least the [S II] temperature¹, whereas densities are lower or equal to those of the inner regions. None of the six selected features of this PN is dominated by shock excitation.

NGC 6891: Spectra were obtained at two position angles, 135° (along the jets) and 45° (from which we analyze the properties of the rim). Table 1 shows that densities and temperatures do not vary (within the errors) at the positions of the rim and the jets. As in the diagnostic diagrams discussed below, the emission of the rim and the jets is dominated by photoionization by the central star.

K 4-47: This is a particularly unusual PN, being mainly composed of an unresolved core and a pair of high velocity blobs, with important differences when compared to the other objects in the sample. First, note that its T_e are very much higher than those of the others, $T_e[\text{O III}]$ always being above $16\,000\text{ K}$ throughout the PN and reaching values as high as $24\,000\text{ K}$ for K1. These temperatures indicate, by themselves, that associated emission should be contaminated or even dominated by shock excitation. If so, the temperature calculation itself would be doubtful. Second, the densities of the knots in K 4-47 are higher than in the core, in such a way that K1 has $N_e[\text{S II}] = 5400\text{ cm}^{-3}$, almost three times the density of the nebular core, while K2 is only 30% denser than the core. Third,

¹ $T_e[\text{S II}]$ is obtained from the $I(6716\text{Å}+6731\text{Å})/I(4069\text{Å}+4076\text{Å})$ line ratio.

the knots of this PN are the only structures in the whole sample that clearly show line ratios characteristics of shock excited emission (see next section).

3. Diagnostic Diagrams

We put in these diagrams the line emission ratios $H\alpha/[N\ II](6548+6583)$ versus $H\alpha/[S\ II](6716+6531)$ and $[O\ III](4959+5007)/H\alpha$ versus $[S\ II](6716+6531)/H\alpha$ (from Phillips & Cuesta 1999) for the different regions of a number of PNe with knots and jets (Figure 3 of Gonçalves's paper, this volume, which contains the PNe discussed here, as well as some others whose data come from the literature). Note that the LIS in He 2-429 and He 1-1 (Guerrero et al. 1999) do not have peculiar velocities with respect to the PNe main bodies in which they are embedded and are useful for comparing their excitation properties with those of the high-velocity features.

These diagrams show that only certain features of K 4-47, KJPn 8, and M 2-48 show evidence for shock excitation. K 4-47 and M 2-48 share many properties with young PNe, such as M 1-16 (Schwarz 1992), being probably the youngest PN in the sample. So far, therefore, our search for the excitation mechanisms of LIS (jets/knots) indicate that in general high-velocity jets/knots in evolved PNe might not be shock excited any longer. Another important thing shown by these diagrams is that properties of the low-velocity features cannot be distinguished from those of the high-velocity ones.

Dopita (1997) and Miranda et al. (2000) have already called our attention to the fact that jets in PNe contain some contribution from shock excitation; however, the main excitation of these jets is radiative. In any case, very strong shocks, like those present in the jets of young stellar objects, clearly do not exist in PNe. Another important issue to investigate is whether the spatial resolution presently available is able to resolve the shocked regions from the generally photoionized extended nebular environment (M. Perinotto, private communication).

References

- Balick, B., Perinotto, M., Maccioni, A., Alexander, Terzian, Y., & Hajian, A. R. 1994, *ApJ*, 424, 800
- Bohigas, J., López, J. A., & Aguilar, L. 1994, *A&A*, 291, 595
- Dopita, M. A. 1997, *ApJ*, 485, L41
- Fernandéz, R., Schwarz, H. E., & Monteiro, H. 2003, *astro-ph/0310076*
- Gonçalves, D. R., Corradi, R. L. M., & Mampaso, A. 2001, *ApJ*, 547, 302
- Gonçalves, D. R., Corradi, R. L. M., Mampaso, A., & Perinotto, M. 2003, *ApJ*, 597, 975
- Guerrero, M. A., Vázquez, R., & López, J. A. 1999, *AJ*, 117, 967
- Hajian, A. R., Balick, B., Terzian, Y., & Perinotto, M. 1997, *ApJ*, 487, 313
- Hyung, S., & Aller, L. H. 1995, *MNRAS*, 273, 958
- Miranda, L. F., et al. 2000, *MNRAS*, 311, 748
- Phillips, J. P., & Cuesta, L. 1999, *AJ*, 118, 2919
- Rubin, R. H., et al. 2002, *MNRAS*, 334, 777
- Schwarz, H. E. 1992, *A&A*, 264, L1